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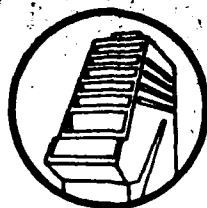
**Adaptive Search Through
Constraint Violations**

Stellan Ohlsson and Ernest Rees

*The Learning Research and Development Center,
University of Pittsburgh,
Pittsburgh, Pennsylvania 15260*

Technical Report No. KUL-90-01
January, 1990

LEARNING RESEARCH AND DEVELOPMENT CENTER



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<p>↓</p> <p>Restructuring consists of a change in the representation of the current search state, a process which breaks an impasse during problem solving by opening up new search paths. A corpus of 52 think-aloud protocols from the domain of geometry was scanned for evidence of restructuring. The data suggest that restructuring is accomplished by re-parsing the geometric diagram.</p>					
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Knowledge and Understanding in Human Learning

Knowledge and Understanding in Human Learning (KUL) is an umbrella term for a loosely connected set of activities lead by Stellan Ohlsson at the Learning Research and Development Center, University of Pittsburgh. The aim of KUL is to clarify the role of *world knowledge* in human thinking, reasoning, and problem solving. World knowledge consists of general principles, and contrasts with facts (episodic knowledge) and with cognitive skills (procedural knowledge). The long-term goal is to answer six questions: How can the conceptual content of a particular knowledge domain be identified? How can a particular person's knowledge of a given domain be diagnosed? How is principled knowledge utilized in insightful performance? How does principled knowledge influence procedure acquisition? How is principled knowledge acquired? How can instruction facilitate the acquisition of principled (as opposed to episodic or procedural) knowledge? Different methodologies are used to investigate these questions: Psychological experiments, computer simulations, historical studies, semantic, logical, and mathematical analyses, instructional intervention studies, etc. A list of KUL reports appear at the back of this report.

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Abstract

We describe HS, a production system that learns control knowledge through adaptive search. Unlike most other psychological models of skill acquisition, HS is a model of analytical, or knowledge-based, learning. HS encodes general domain knowledge in *state constraints*, patterns that describe those search states that are consistent with the principles of the problem domain. When HS encounters a search state that violates a state constraint, it revises the production rule that generated that state. The appropriate revisions are computed by regressing the constraint through the action of the production rule. HS can learn to solve problems that it cannot solve without learning. We present a Blocks World example of a rule revision, empirical results from both initial learning experiments and transfer experiments in the domain of counting, and an informal analysis of the conditions under which this learning technique is likely to be useful.

Introduction

The acquisition of control knowledge is a central problem in machine learning research. In one formulation of the control knowledge problem, a weak but general problem solver searches for the solution to a problem with an initial set of incomplete or faulty problem solving rules. Learning mechanisms such as discrimination (Langley, 1985), subgoalting (Ohlsson, 1987a), or version spaces (Mitchell, 1982) can be applied to the information in the search tree to identify conditions that will enable the rules to solve the problem, or the relevant class of problems, with less search. Psychologists are interested in this learning scenario because it offers a possible model of how humans learn cognitive skills through practice (see, e. g., Anderson, 1989; Holland, Holyoak, Nisbett, & Thagard, 1986; Laird, Rosenbloom, & Newell, 1986; VanLehn, in press).

Psychological models of skill acquisition employ different problem solving mechanisms (forward search, backward chaining, means-ends analysis, planning, universal weak method) and different learning mechanisms (analogy, chunking, composition, discrimination, grammar induction, subgoalting), but with only a few exceptions (Anderson, 1989; Ohlsson, 1987b; Ohlsson & Rees, 1988) they have focussed on *empirical* learning methods. They identify rule conditions by performing some form of induction (in a broad sense) on the examples of correct and incorrect operator applications embedded in the search tree. Empirical learning methods contrast with *analytical* methods such as explanation-based learning (EBL) which identify rule conditions by applying knowledge about the relevant problem domain (Minton, 1988). But analytical learning methods are particularly interesting from a psychological point of view, because they offer a possible explanation of the facilitating effect of domain knowledge on procedure acquisition. Psychological experiments have shown that knowledge of the principles of a domain enables people to learn procedures faster and apply them more flexibly (see, e. g., Kieras & Bovair, 1984) as compared to conditions in which such knowledge is absent.

We describe a technique for knowledge-based procedure acquisition which is based on the idea that the main function of knowledge is to constrain the possible states of affairs. Incomplete control knowledge will frequently lead to the generation of search states that violate such constraints. The information contained in constraint violations can be used to identify new rule conditions adaptively, before a correct solution path has been found (Mostow & Bhatnager, 1986). The technique is implemented in a running simulation model called HS. We present data from both initial learning experiments and transfer experiments, and an informal analysis of the conditions under which our learning technique is likely to be useful. Our system is related to the FAILSAFE system described by Mostow and Bhatnager (1986), to the proceduralization hypothesis proposed by Anderson (1989), and to the planning net model of counting competence put forward by Smith, Greeno, and Vitolo (in press). A comparison with these systems will be postponed until the discussion section.

Knowledge as Constraints on Possible Situations

We are interested in the cognitive function of general knowledge. Many discussions of knowledge implicitly assume that the function of general knowledge is either to summarize particular facts or to enable explanations and predictions. There is no doubt that knowledge has those functions. However, we want to suggest that knowledge *also* can have the function of constraining the set of situations that one can reasonably expect to happen. The laws of conservation of mass and energy and the laws of commutativity and associativity of addition are examples of general principles that constrain the possible states of affairs. Faulty control knowledge, e. g., an incorrect laboratory procedure or a buggy addition algorithm, is likely to lead to violations of such constraints.

To capture the idea of general knowledge as constraints on possible situations, we encode a principle *C* as a *state constraint*, i. e., as an ordered pair of patterns $\langle C_r, C_s \rangle$ in which C_r is the *relevance pattern* and C_s is the *satisfaction pattern*. For example, the law of commutativity of addition expressed as a state constraint becomes *if $x + y = p$ and $y + x = q$, then it should be the case that $p = q$* . The principle of one-to-one mapping becomes *if object A has been assigned to object B, then there should not be some other object X which also has been assigned to B*. The law of conservation of mass becomes *if M_1 is the mass of the ingredients in a chemical experiment, and M_2 is the mass of the products, then it should be the case that $M_1 = M_2$* . A constraint consists of a pair of patterns because all constraints are not relevant for all problem types. The relevance pattern of a state constraint specifies those search states (situations) in which the corresponding principle applies. The purpose of expressing domain knowledge in state constraints is to enable the HS system to efficiently identify search states that violate principles of the domain. This requires a $\text{MATCH}(C, S)$ predicate that can decide whether a given pattern matches a given search state. We have used a RETE pattern matcher (Forgy, 1982) as our MATCH predicate.

HS is a relatively standard production system architecture that has been augmented with the state constraint representation. The system is given a problem space (an initial state, a set of operators, and a goal criterion), and a set of (minimally constrained) production rules. The initial state is a fully instantiated description of the problem, an operator consists of an addition list and a deletion list, and the goal criterion is a pattern. The system solves problems by forward breadth-first search through the problem space. Forward search is a very weak method, but since HS searches adaptively (Mostow & Bhatnager, 1987), improving its rules before it has found a complete solution path, it need not search the problem space exhaustively. HS searches until it encounters a constraint violation, learns from that violation, backs up to the initial state, and tries anew to solve the problem. If a state violates more than one constraint, HS selects one at random to learn from.

The identification of constraint violations proceeds as follows. When a production rule $P: R \rightarrow O$ with condition *R* and action *O* is applied to a search state S_1 , thereby generating a descendent state S_2 , the relevance patterns of all constraints are matched against the new state S_2 . If the relevance pattern C_r of constraint *C* does not match S_2 , then *C* is irrelevant for that state and no further action is taken with respect to that constraint; if C_r does match, then *C* is relevant and the satisfaction pattern C_s is also

matched against S_2 . If C_s matches, no further action is taken. But if C_s does not match, then a constraint violation is recorded. State constraints do not generate conclusions or fire operators; nothing is added to the problem description when a state constraint is applied. A state constraint functions as a classification device that sorts search states into those that are consistent with the principles of the domain and those that are not.

Learning from Constraint Violations

There are two types of constraint violations in the HS system. Suppose that production rule $P: R \rightarrow O$ was evoked in state S_1 , leading to the generation of a new state S_2 . In a *Type A* violation the constraint C is irrelevant in S_1 , and it is relevant but not satisfied in S_2 . In a *Type B* violation the constraint C is both relevant and satisfied in S_1 , and it is relevant but not satisfied in S_2 . Each type violation requires two different revisions of the rule P . The new rules are computed by regressing the constraint through the operator, but we will explain the technique with a set-theoretic notation which shows clearly why each type of violation gives rise to two new rules.

Rule revisions for Type A violations. If the relevance pattern C_r does not match state S_1 , but does match its immediate descendent S_2 , then the effect of operator O is to create expressions that enable C_r to match. But since, *ex hypothesi*, the constraint C is violated in S_2 , O does not create the expressions needed to complete the match for the satisfaction pattern C_s . This situation warrants two different revisions of the rule P that fired O . First, the condition of P should be revised so that the revised rule--call it P' --only matches in situations in which O does not complete the relevance pattern for C , thus ensuring that the constraint remains irrelevant. Second, the condition of P should be revised so that the revised rule--call it P'' --only fires in those situations in which *both* the relevance *and* the satisfaction patterns of C are completed, thus ensuring that the constraint becomes satisfied.

Revision 1. Ensuring that the constraint remains irrelevant. O will complete C_r when the parts of C_r that are not added by O are already present in S_1 . Those parts are given by $(C_r - O_a)$, where the symbol "-" signifies set difference. To limit the application of rule P to situations in which operator O will not complete C_r , we augment the condition of P with the negated expression *not* $(C_r - O_a)$. The new rule is

$$P': R \ \& \ \text{not} \ (C_r - O_a) \rightarrow O$$

where "&" signifies conjunction.

Revision 2. Ensuring that the constraint becomes satisfied. To guarantee that C_r will become complete, we augment the condition R with $(C_r - O_a)$. To guarantee that C_s will also become complete we augment R with those parts of C_s that are not added by O . They are given by $(C_s - O_a)$, so the desired effect is achieved by adding the entire expression $(C_r - O_a) \cup (C_s - O_a)$ to R , where the symbol " \cup " signifies set union. The new rule is

$$P'': R \cup (C_r - O_a) \cup (C_s - O_a) \rightarrow O$$

Rule revisions for Type B violations. If the constraint C is both relevant and satisfied in state S_1 , and relevant but not satisfied in S_2 , the effect of operator O is to destroy the match for the satisfaction pattern C_s , but not for the relevance pattern C_r . This situation also warrants two revisions of rule P.

Revision 1. Ensuring that the constraint is irrelevant. Rule P is revised so that it will only fire in situations in which constraint C is not relevant and in which C will not become relevant. This is accomplished by adding the negation of the relevance pattern C_r to the condition R of the rule. The new rule is

$$P': R \& \text{not } C_r \rightarrow O$$

Revision 2. Ensuring that the constraint remains satisfied. Rule P is replaced by a rule P'' which only fires in situations in which the constraint remains satisfied. This is done in two steps. The first step is to constrain the rule to fire only in situations in which the constraint is relevant. This is accomplished by adding the relevance pattern C_r to the rule condition. The second step is to constrain the rule to situations in which the match of the satisfaction pattern is unaffected by the action of operator O. This is accomplished by adding the negation of the intersection between the satisfaction pattern and the deletion list, $\text{not}(C_s \cap O_d)$, to the rule condition. The desired effect is attained by adding the entire expression $C_r \cup \text{not}(C_s \cap O_d)$, so the new rule is

$$P'': R \cup C_r \cup \text{not}(C_s \cap O_d) \rightarrow O.$$

The above description of the learning algorithm is simplified in the following respects: (a) Rules are not replaced by their descendents. The old rules are retained, but their descendents are preferred during conflict resolution. (b) In order to add parts of a constraint to a rule condition correspondances must be computed between the variables in the constraint and the variables in the rule. In the implementation those correspondances are computed by the regression algorithm. (c) A negated condition can cease to match as the result of the addition of expressions to a search state. Our revision algorithm handles those cases as well. (d) There are cases in which one of the two revisions results in the empty list of new conditions. In those cases only one new rule is created.

Revising a Blocks World Rule

The HS system has mainly been applied to arithmetic tasks such as counting a collection of objects, and subtracting multi-digit integers (Ohlsson & Rees, 1988). We nevertheless illustrate the rule revision algorithm with an example from the Blocks World, because of the widespread familiarity with this domain. Successful performance in the Blocks World requires knowledge of where blocks can be put down. Putting a block on the table or on top of a stack generally results in a stable situation, but trying to put a block on another block that already has other blocks stacked on top of it is likely to lead to the collapse of the stack. The following Blocks World rule says that *if the hand is holding a block, and the goal is to put*

the block down, and the hand is in the up position, and there is a possible support, then lower the hand:

```
(GOAL PUTDOWN <Block>)(ISA BLOCK <Block>)(HOLDING HAND <Block>)
(POSITION HAND UP)(ISA SUPPORT <Support>)
-->
LowerHand(<Block>, <Support>)
```

The operator LowerHand lowers the block onto the support, but does not let go of the block. It is defined by the deletion list

$$O_d = \{(POSITION\ HAND\ UP)\}$$

and the addition list

$$O_a = \{(POSITION\ HAND\ DOWN)(ON\ <Block>\ <Support>)\}.$$

Since blocks are members of the category *supports*, this rule will attempt to lower the block onto any other block in the world. If the supporting block is in the middle of a stack, this operation violates the principle that *only one block can be on top of another block*, which can be expressed as a state constraint with relevance pattern

$$C_r = \{(ON\ <Block>\ <Support>)(ISA\ BLOCK\ <Support>)\}$$

and satisfaction pattern

$$C_s = \{(not\ (ON\ <OtherBlock>\ <Support>)\ (not\ (EQUAL\ <OtherBlock>\ <Block>)))\}$$

Lowering a block until it rests on a block that is not a top block, i. e., a block which has other blocks resting on it, leads to a violation of this constraint. Since the constraint cannot be relevant before the hand is lowered, this is a Type A violation.

Revision 1. Ensuring that the constraint remains irrelevant. The difference between the relevance pattern C_r and the addition list O_a is

$$C_r - O_a = \{(ISA\ BLOCK\ <Block>)\}.$$

The negation of this expression is added to the rule condition, so the new rule becomes:

```
(Goal: PUTDOWN <Block>)(ISA BLOCK <Block>)(HOLDING HAND <Block>)
(POSITION HAND UP)(ISA SUPPORT <Support>)
(not (ISA BLOCK <Support>))
-->
LowerHand(<Block>)
```

where the new condition is in boldfaced typefont. This rule says that it is possible to put a block down on any support that is not a block. In the standard version of the Blocks World, the only support that is not a block is the table.

Revision 2. Ensuring that the constraint becomes satisfied. As noted above the difference $(C_r - O_a)$ is in this case

$$C_r - O_a = \{(ISA\ BLOCK\ <Support>)\}.$$

Subtracting the addition list O_a from the satisfaction pattern C_s returns the satisfaction pattern itself,

because they do not have any expressions in common in this case. Adding $\{(C_r - O_a) \cup (C_s - O_a)\}$ to the rule therefore generates the new rule

```
(Goal: PUTDOWN <Block>)(ISA BLOCK <Block>)(HOLDING HAND <Blocks>)
(POSITION HAND UP)(ISA SUPPORT <Support>)
(ISA BLOCK <Support>)
(not [(ON <OtherBlock> <Support>)(not (EQUAL <OtherBlock> <Block>))])

-->
LowerHand(<Block>, <Support>)
```

where the new conditions are in boldfaced typefont. This rule says a block can be lowered onto another block, if that other block is a top block, i. e., if it does not have any blocks resting on it.

In summary, the revision algorithm takes as input a violation of the constraint *only one block can be on top of another block* and sorts out the two action possibilities that are consistent with it--either put a block down on the table, or put it down on a top block--encoding each possibility in a separate production rule. The two new rules are not perfect, of course, and they will be revised further when they violate other constraints. Repeated revision of rules is a central feature of learning in the HS system.

Evaluation

The task of quantifying a collection of objects by counting them is interesting from the point of view of the cognitive function of principled knowledge, because observations of children show that they understand the principles that underly counting (Gelman & Gallistel, 1978; Gelman & Meck, 1986). Modifying slightly the analysis by Gelman and Gallistel (1978), we identify three counting principles: (a) *The Regular Traversal Principle* which says that correct counting begins with unity and generates the natural numbers in numerical order. (b) *The One-One Mapping Principle* which says that each object should be assigned exactly one number during counting. (c) *The Cardinality Principle* which says that the last number to be assigned to an object during counting represents the numerosity of the counted collection. These three principles form the conceptual basis of the procedure for *standard counting*, in which the objects are counted in any order. In order to probe children's understanding of counting, Gelman and Gallistel (1978) invented two non-standard counting tasks, *ordered counting*, in which the objects are counted in some pre-defined order (e.g., from left to right), and *constrained counting*, in which the objects are counted in such a way that a designated object is assigned a designated number. These three counting tasks require different procedures (control knowledge), but all three procedures are based on the above principles.

HS can learn the correct procedure for either of the three counting tasks. The input to the system consists of a problem space for counting, state constraint representations of the counting principles, and an initial rule set. Our representation for the counting task is very fine-grained, and the operations of setting and retracting goals are treated as search steps, so counting three objects requires 48 steps through the problem space. Since the initial rules are minimal, the branching factor before learning is between two and four, giving a search space of more than $60 \cdot 10^9$ states. This search problem is too large

Table 1: Initial Learning Effort for Three Counting Tasks.

Counting task	Effort measure		
	Rule revisions	Production system cycles	Search states
Standard	12	854	979
Ordered	11	262	294
Constrained	12	451	507

to be solved by brute force, but since HS searches adaptively, the system is nevertheless successful. Table 1 show three measures of the amount of work required to learn each counting procedure. The number of rule revisions required is approximately the same (either 11 or 12) for each procedure. The number of states visited during learning is less than 10^3 , so the system only needs to visit a very small portion of the total search space in order to find those rule revisions. In terms of either the number of production system cycles or the number of search states visited, standard counting is harder to learn than constrained counting, which in turn is harder to learn than ordered counting, a prediction which in principle is empirically testable.

Observations of children show that they can easily switch from standard counting to either of the two non-standard counting tasks (Gelman & Gallistel, 1978; Gelman & Meck, 1986). The most plausible explanation for this flexibility is that children can derive the control knowledge for the non-standard counting tasks from their knowledge of the counting principles. To simulate this flexibility we performed transfer experiments with HS. Once the system had learned a correct counting procedure, we gave it counting problems of a different type than the type on which it had practiced. For example, having practiced on standard counting, the system might be given constrained counting problems, and vice versa. To solve these problems the system had to adapt the already learned control knowledge to the new task. Since there are three different counting tasks, there are six possible transfers, all of which HS carried out successfully. Table 2 shows three measures of the amount of work required for each of the six transfers.

Three conclusions emerge from Table 2. First, the number of rule revisions is between one order of magnitude lower than the number of production system cycles or the number of search states visited, so HS predicts that the density of learning events during practice is low. Second, there is substantial transfer between the three counting tasks. The number of rule revisions required to learn any one of the three counting tasks from scratch is either 11 or 12; the number of revisions required to transfer to a different task is between 0 and 3 in five cases, a saving of approximately 75 %. Third, transfer is asymmetric. Ordered counting does not transfer to constrained counting, but constrained counting transfers very well

Table 2: Learning Effort for Six Transfer Tasks in the Counting Domain.

Training task	Transfer task		
	Standard counting	Ordered counting	Constrained counting
Standard			
Revisions	-	2	2
Cycles	-	110	127
States	-	119	141
Ordered			
Revisions	1	-	11
Cycles	184	-	297
States	209	-	334
Constrained			
Revisions	0	3	-
Cycles	162	154	-
States	180	190	-

to ordered counting. Although we do not yet possess the relevant observations, these predictions are in principle empirically testable.

Discussion and Related Work

In which task domains is constraint violation likely to be effective? The technique allows a system to identify, out of all possible paths in a search space, those paths which are consistent with the principles of the task domain. Let us call those *correct* paths. A correct path is not necessarily a *useful* path, i. e., a path that leads to a desired problem solution. Constraint violation is likely to be effective when (a) the ratio of correct to possible paths is small, i. e., when correct paths are rare, and (b) the ratio of useful to correct paths is high, i. e., when many correct paths are useful. In the counting domain *every* step is regulated by the counting principles, so every correct path is also a useful path. Another domain in which constraint violation might be useful is predicting the outcomes of chemical experiments, where all reaction paths that are consistent with the laws of chemistry need to be considered. But in proof spaces in algebra and geometry, where there are many mathematically correct paths which do not lead to a desired theorem, constraint violation is likely to be ineffective.

Our system is similar in basic conception to the FAILSAFE system described by Mostow and Bhatnager (1987) that operates in a floor planning domain. Both systems learn control knowledge during forward

search by using the information in failed solution paths to revise the rules that lead to those paths. Both systems encode domain knowledge as constraints on correct solutions, and both systems use regression to identify the new rule conditions. However, there are also differences. First, Mostow and Bhatnager (1987) argue that one of the advantages of adaptive search is that it becomes possible to make progress on problems for which the completion of a correct solution path through unconstrained search is infeasible. However, this advantage does not seem to be realized in the FAILSAFE system, since the system in fact completes an entire floorplan before testing whether it satisfies the constraints. The HS system applies its constraints after each problem solving step, and it learns before it has completed a correct solution. Second, the FAILSAFE system relies on the fact that the length of a floor plan solution is known *a priori* to identify failures. In contrast, the state constraint representation provides HS with a general method for identifying failures. Third, the FAILSAFE system learns one new rule for each failure, while HS learns two new rules in response to each constraint violation. The cause of this difference deserves to be analyzed in more detail than we can do here. Fourth, like other EBL systems, FAILSAFE uses its domain theory to construct explanations, a potentially complicated process which might require search, and which might fail if the domain theory is incorrect or incomplete. HS replaces the construction of explanations with pattern matching. Fifth, the FAILSAFE system can assign blame to rules which are several steps removed from the point of failure detection. This is an advance upon the HS system, in which blame is always assigned to the last rule to fire before failure detection.

Psychological models of learning do not usually address the problem of the cognitive function of general knowledge in procedure acquisition. One exception is the ACT* theory proposed by Anderson (1989), which claims that declarative knowledge structures are *proceduralized* during problem solving. The main difference between proceduralization and constraint violation is that in proceduralization declarative knowledge only participates in the creation of *initial* rules; further improvement of those rules is handled by empirical learning mechanisms such as composition and strengthening. In constraint violation declarative knowledge continues to influence rule revisions during the entire life time of the rule. The planning net model of counting competence proposed by Smith, Greeno, and Vitolo (in press) addresses the same phenomenon as the HS system--children's flexibility in moving between different counting tasks--and their model also assumes that the source of this flexibility is a declarative encoding of the counting principles. However, Smith, Greeno, and Vitolo (in press) characterize their model as a competence model rather than as a process model, disclaiming any psychological reality for the processes they describe. It is therefore unclear how to conduct a comparison between their system and ours.

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20122 Milano - via F. Sforza 23
ITALY

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80 Glenn Avenue
Berwyn, PA 19312

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Department of Computer Science
Box 1688, Station B
Vanderbilt University
Nashville, TN 37235

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Teachers College, Box 8
Columbia University
525 West 120th Street
New York, NY 10027

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Code 943
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San Diego, CA 92152-5000

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Orlando, FL 32813-7100

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George Mason University
4400 University Drive
Fairfax, VA 22030

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Stanford, CA 94305

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Center for the Study of Reading
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51 Gerry Drive
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Center for Research into Practice
3545 Albemarle Street, NW
Washington, DC 20008

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Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Gail Carpenter
Center for Adaptive Systems
111 Cummington St., Room 244
Boston University
Boston, MA 02215

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2600 Camino Ramon
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818 South George Mason Drive
Arlington, VA 22204

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Department of Psychology
Univ. of So. California
Los Angeles, CA 90089-1061

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Office of Naval Technology
Code 222
800 N. Quincy Street
Arlington, VA 22217-5000

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Cornell University
Dept. of Education
Room 490 Roberts
Ithaca, NY 14853

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Training Technology Branch
3400 TCHTW/TTGXC
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Department of Psychology
Tallahassee, FL 32306

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PO Box 748/Mail Zone 2646
Fort Worth, TX 76101

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Suite 1209
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Navy Personnel R&D Center
Code 51
San Diego, CA 92252

Dr. Susan Epstein
144 S. Mountain Avenue
Montclair, NJ 07042

ERIC Facility-Acquisitions
2440 Research Blvd, Suite 550
Rockville, MD 20850-3238

Dr. K. Anders Ericsson
University of Colorado
Department of Psychology
Campus Box 345
Boulder, CO 80309-0345

Dr. Debra Evans
Applied Science Associates, Inc.
P. O. Box 1072
Butler, PA 16003

Dr. Lorraine D. Eyde
Office of Personnel Management
Office of Examination Development
1900 E St., NW
Washington, DC 20415

Dr. Jean-Claude Falmagne
Irvine Research Unit in
Mathematical & Behavioral Sciences
University of California
Irvine, CA 92717

Dr. Beatrice J. Farr
Army Research Institute
PERI-IC
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Marshall J. Farr, Consultant
Cognitive & Instructional Sciences
2520 North Vernon Street
Arlington, VA 22207

Dr. P.-A. Federico
Code 51
NPRDC
San Diego, CA 92152-6800

Dr. Jerome A. Feldman
University of Rochester
Computer Science Department
Rochester, NY 14627

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Boulder, CO 80309

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Dept. of Educational Psychology
McGill University
3700 McTavish Street
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CANADA H3A 1Y2

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Cambridge, MA 02238

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University of Alberta
Edmonton, Alberta
CANADA T6G 2E9

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Psychology Department
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CANADA M3J 1P3

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1456 Mitchell Avenue
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AFOSR/NE, Bldg. 410
Bolling AFB
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Dr. Philip Gillis
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Fort Gordon, GA 30905

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305 Davis Avenue
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Dr. Robert Glaser
Learning Research
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3939 O'Hare Street
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ARI Field Unit
P.O. Box 5787
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Computer Science Laboratory
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Bldg. 42, Room B2
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Dr. T. Govindaraj
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Artificial Intelligence Laboratory
NYNEX
500 Westchester Avenue
White Plains, NY 10604

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Dep Asst C/S, Instructional
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Quantico, VA 22134-5050

Dr. Dik Gregory
Admiralty Research
Establishment/AXB
Queens Road
Teddington
Middlesex, ENGLAND TW110LN

Dr. Stephen Grossberg
Center for Adaptive Systems
Room 244
111 Cushing Street
Boston University
Boston, MA 02215

Michael Habon
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D-7990 Friedrichshafen 1
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55 Chapel Street
Newton, MA 02160

Dr. Barbara Hayes-Roth
Knowledge Systems Laboratory
Stanford University
701 Welch Road
Palo Alto, CA 94304

Dr. Frederick Hayes-Roth
Teknowledge
P.O. Box 10119
1850 Embarcadero Rd.
Palo Alto, CA 94303

Dr. James Hendler
Dept. of Computer Science
University of Maryland
College Park, MD 20742

Dr. James Hiebert
Department of Educational
Development
University of Delaware
Newark, DE 19716

Dr. Geoffrey Hinton
Computer Science Department
University of Toronto
Sandford Fleming Building
10 King's College Road
Toronto, Ontario M5S 1A4 CANADA

Dr. James E. Hoffman
Department of Psychology
University of Delaware
Newark, DE 19711

Dr. Keith Holyoak
Department of Psychology
University of California
Los Angeles, CA 90024

Ms. Julia S. Hough
Cambridge University Press
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Chief Scientist
AFHRL/CA
Brooks AFB, TX 78235-5601

Dr. Steven Hunka
3-104 Educ. N.
University of Alberta
Edmonton, Alberta
CANADA T6G 2G5

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2122 Coolidge Street
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Wean Hall 8124
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Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

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University of Minnesota
Department of Psychology
Elliott Hall
75 E. River Road
Minneapolis, MN 55455

Dr. Michael Kaplan
Office of Basic Research
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. A. Karmiloff-Smith
MRC-CDU
17 Gordon Street
London
ENGLAND WC1H 0AH

Dr. Milton S. Katz
European Science Coordination
Office
U.S. Army Research Institute
Box 65
FPO New York 09510-1500

Dr. Frank Keil
Department of Psychology
228 Uris Hall
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IBM T. J. Watson Research Ctr.
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Yorktown Heights, NY 10598

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University of North Carolina
Department of Statistics
Chapel Hill, NC 27514

Dr. David Kieras
Technical Communication Program
TIDAL Bldg., 2360 Bonisteel Blvd.
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Dr. Jeremy Kilpatrick
Department of
Mathematics Education
105 Aderhold Hall
University of Georgia
Athens, GA 30602

Dr. J. Peter Kincaid
Army Research Institute
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c/o PM TRADE-E
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Dr. Walter Kintsch
Department of Psychology
University of Colorado
Boulder, CO 80309-0345

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Georgia Institute of
Technology
Center for Human-Machine
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Atlanta, GA 30332-0205

Dr. Janet L. Kolodner
Georgia Institute of Technology
School of Information
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Atlanta, GA 30332

Dr. Stephen Kosslyn
Harvard University
1234 William James Hall
33 Kirkland St.
Cambridge, MA 02138

Dr. Kenneth Kotovsky
Community College of
Allegheny County
808 Ridge Avenue
Pittsburgh, PA 15212

Dr. Keith Kramer
HCI Lab, Code 5530
Naval Research Laboratory
4445 Overlook Avenue
Washington, DC 20375-5000

Dr. Gary Kress
628 Spitzer Avenue
Pacific Grove, CA 93950

Dr. Lois-Anne Kuntz
3010 S.W. 23rd Terrace
Apt. No. 105
Gainesville, FL 32608

Dr. David R. Lambert
Naval Ocean Systems Center
Code 772
271 Catalina Boulevard
San Diego, CA 92152-5000

Dr. Pat Langley
NASA Ames Research Ctr.
Moffett Field, CA 94035

Dr. Robert W. Lawler
Matthews 118
Purdue University
West Lafayette, IN 47907

Dr. Eugene Lee
Naval Postgraduate School
Monterey, CA 93943-5026

Dr. Yuh-Jeng Lee
Department of Computer Science
Code 52La
Naval Postgraduate School
Monterey, CA 93943

Dr. Jill F. Lehman
School of Computer Science
Carnegie Mellon University
Pittsburgh, PA 15213-3890

Dr. Jim Levin
Department of
Educational Psychology
210 Education Building
1310 South Sixth Street
Champaign, IL 61820-6990

Dr. John Levine
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Pittsburgh, PA 15260

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Carnegie-Mellon University
Pittsburgh, PA 15213

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Software Productivity Consortium
1880 Campus Commons Drive, North
Reston, VA 22091

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Graduate School
of Education, EMST
Tolman Hall
University of California
Berkeley, CA 94720

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Dept. of Geography
University of South Carolina
Columbia, SC 29208

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University of
Massachusetts
Physics Department
Amherst, MA 01003

Vern M. Malec
NPRDC, Code 52
San Diego, CA 92152-6800

Dr. William L. Maloy
Code 04
NETPMSA
Pensacola, FL 32509-5000

Dr. Mary Martino
Director, Educational Technology
HQ USAFA/DFTE
USAF Academy, CO 80840-5000

Dr. Sandra P. Marshall
Dept. of Psychology
San Diego State University
San Diego, CA 92182

Dr. John H. Mason
Centre for Maths Education
Mathematics Faculty
Open University
Milton Keynes MK7 6AA
UNITED KINGDOM

Dr. Manton M. Matthews
Department of Computer Science
University of South Carolina
Columbia, SC 29208

Dr. Richard E. Mayer
Department of Psychology
University of California
Santa Barbara, CA 93106

Dr. David J. McGuinness
Gallaudet University
800 Florida Avenue, N.E.
Washington, DC 20002

Dr. Joseph C. McLachlan
Code 52
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Douglas L. Medin
Department of Psychology
University of Michigan
Ann Arbor, MI 48109

Mr. Stig Meincke
Forbaret Center for Ledenskab
Christianshavns Voldgade 8
1424 Kobenhavn K
DENMARK

Dr. Arthur Melmed
Computer Arts and
Education Laboratory
New York University
719 Broadway, 12th floor
New York, NY 10003

Dr. Jose Mestre
Department of Physics
Hasbrouck Laboratory
University of Massachusetts
Amherst, MA 01003

Dr. D. Michie
The Turing Institute
George House
36 North Hanover Street
Glasgow G1 2AD
UNITED KINGDOM

Dr. Vittorio Midoro
CNR-Istituto Tecnologie Didattiche
Via All'Opera Pia 11
GENOVA-ITALIA 16145

Dr. James R. Miller
MOC
3500 W. Balcones Center Dr.
Austin, TX 78759

Dr. Jason Millman
Department of Education
Roberts Hall
Cornell University
Ithaca, NY 14853

Dr. Christine M. Mitchell
School of Indus. and Sys. Eng.
Center for Man-Machine
Systems Research
Georgia Institute of Technology
Atlanta, GA 30532-0205

Dr. Andrew R. Molnar
Applic. of Advanced Technology
Science and Engr. Education
National Science Foundation
Washington, DC 20550

Dr. William Montague
NPRDC Code 13
San Diego, CA 92152-6800

Dr. Melvin D. Montemario
NASA Headquarters
Code RC
Washington, DC 20546

Prof. John Morton
MRC Cognitive
Development Unit
17 Gordon Street
London WC1H 0AH
UNITED KINGDOM

Dr. Allen Munro
Behavioral Technology
Laboratories - USC
250 N. Harbor Dr., Suite 309
Redondo Beach, CA 90277

Dr. William R. Murray
FMC Corporation
Central Engineering Labs
1205 Coleman Avenue
Box 580
Santa Clara, CA 95052

Chair, Department of Weapons and
Systems Engineering
U.S. Naval Academy
Annapolis, MD 21402

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Dr. Harold F. O'Neill, Jr.
School of Education - WPH 801
Department of Educational
Psychology & Technology
University of Southern California
Los Angeles, CA 90089-0031

Dr. Paul O'Rourke
Information & Computer Science
University of California, Irvine
Irvine, CA 92717

Dr. Stellan Obitson
Learning R & D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. James B. Olson
WICAT Systems
1875 South State Street
Orem, UT 84058

Dr. Gary M. Olson
Cognitive Science and
Machine Intelligence Lab
University of Michigan
701 Tappan Street
Ann Arbor, MI 48109-1234

Dr. Judith Reisman Olson
Graduate School of Business
University of Michigan
Ann Arbor, MI 48109-1234

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800 N. Quincy Street
Arlington, VA 22217-5000
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Dr. Judith Oransou
Basic Research Office
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Jesse Oransky
Institute for Defense Analyses
1801 N. Beauregard St.
Alexandria, VA 22311

Dr. Everett Palmer
Mail Stop 239-3
NASA-Ames Research Center
Moffett Field, CA 94035

Dr. Otchobon Park
Army Research Institute
PERJ-2
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Roy Pass
Institute for Research
on Learning
2550 Hanover Street
Palo Alto, CA 94304

Dr. David N. Pertins
Project Zero
Harvard Graduate School
of Education
7 Appian Way
Cambridge, MA 02138

Dr. C. Perrino, Chair
Dept. of Psychology
Morgan State University
Cold Spring La.-Hillen Rd.
Baltimore, MD 21239

Dr. Nancy N. Perry
Naval Education and Training
Program Support Activity
Code-047
Building 2435
Pensacola, FL 32509-5000

Dept. of Administrative Sciences
Code 54
Naval Postgraduate School
Monterey, CA 93943-5026

Dr. Peter Pirotti
School of Education
University of California
Berkeley, CA 94720

Prof. Tomaso Poggio
Massachusetts Institute
of Technology E25-201
Center for Biological
Information Processing
Cambridge, MA 02139

Dr. Peter Polson
University of Colorado
Department of Psychology
Boulder, CO 80309-0345

Dr. Steven E. Poltrock
Boeing Advanced Technology Center
PO Box 24346 m/s 7L-64
Seattle, WA 98124

Dr. Joseph Protka
ATTN: PERI-IC
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333-5600

Mr. Paul S. Rau
Code U-33
Naval Surface Weapons Center
White Oak Laboratory
Silver Spring, MD 20903

Dr. James A. Reggia
University of Maryland
School of Medicine
Department of Neurology
22 South Greene Street
Baltimore, MD 21201

Dr. J. Wesley Regan
AFHRL/IDI
Brooks AFB, TX 78235

Dr. Fred Reif
Physics Department
University of California
Berkeley, CA 94720

Dr. Charles M. Reigeluth
330 Huntington Hall
Syracuse University
Syracuse, NY 13244

Dr. Daniel Reisberg
Reed College
Department of Psychology
Portland, OR 97202

Dr. Lauren Resnick
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

Dr. J. Jeffrey Richardson
Center for Applied AI
College of Business
University of Colorado
Boulder, CO 80309-0419

Dr. Edwin L. Risaland
Dept. of Computer and
Information Science
University of Massachusetts
Amherst, MA 01003

Mr. William A. Rizzo
Code 71
Naval Training Systems Center
Orlando, FL 32813

Dr. Linda G. Roberts
Science, Education, and
Transportation Program
Office of Technology Assessment
Congress of the United States
Washington, DC 20510

Dr. Ernst Z. Rothkopf
AT&T Bell Laboratories
Room 2D-456
600 Mountain Avenue
Murray Hill, NJ 07974

Dr. Alan H. Schoenfeld
University of California
Department of Education
Berkeley, CA 94720

Lowell Schoer
Psychological & Quantitative
Foundations
College of Education
University of Iowa
Iowa City, IA 52242

Dr. Janet W. Schofield
816 LRDC Building
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Kay Schulze
Computer Science Dept.
U.S. Naval Academy
Annapolis, MD 21402-5018

Dr. Miriam Schustack
Code 52
Navy Personnel R & D Center
San Diego, CA 92152-6800

Dr. Judith W. Segal
OERI
555 New Jersey Ave., NW
Washington, DC 20208

Dr. Robert J. Seidel
US Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333

Dr. Colleen M. Seifert
Institute for Cognitive Science
Mail Code C-015
University of California, San Diego
La Jolla, CA 92093

Dr. Michael G. Shaflo
NASA Ames Research Ctr.
Mail Stop 239-1
Moffett Field, CA 94035

Mr. Colin Sheppard
AXC2 Block 3
Admiralty Research Establishment
Ministry of Defence Portdown
Portsmouth Hants PO64AA
UNITED KINGDOM

Dr. Lee S. Shulman
School of Education
507 Cerna
Stanford University
Stanford, CA 94305-5084

Dr. Randall Shumaker
Naval Research Laboratory
Code 5510
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

Dr. Edward Silver
LRDC
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Herbert A. Simon
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Robert L. Simpson, Jr.
DARPA/ISTO
1400 Wilson Blvd.
Arlington, VA 22209-2308

Dr. Zita M. Simutis
Chief, Technologies for Skill
Acquisition and Retention
ARI
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Derek Sleeman
Computing Science Department
The University
Aberdeen AB9 2FX
Scotland
UNITED KINGDOM

Ms. Gail K. Slemmon
LOGICON, Inc.
P.O. Box 85158
San Diego, CA 92138-5158

Dr. Edward E. Smith
Department of Psychology
University of Michigan
330 Packard Road
Ann Arbor, MI 48103

Dr. Alfred F. Smode
Code 7A
Research and Development Dept.
Naval Training Systems Center
Orlando, FL 32813-7100

Dr. Elliot Soloway
Yale University
Computer Science Department
P.O. Box 2158
New Haven, CT 06520

Linda B. Sorasio
IBM-Los Angeles Scientific Center
1601 Wilshire Blvd., 4th Floor
Los Angeles, CA 90025

N. S. Sridharan
FMC Corporation
Box 580
1205 Coleman Avenue
Santa Clara, CA 95052

Dr. Marian Stearns
SRJ International
333 Ravenswood Ave.
Room B-5124
Menlo Park, CA 94025

Dr. Friedrich W. Steege
Bundesministerium
des Verteidigung
Postfach 1328
D-5300 Bonn 1
WEST GERMANY

Dr. Frederick Steinbesser
CLA-ORD
Ames Building
Washington, DC 20505

Dr. Saul Sternberg
University of Pennsylvania
Department of Psychology
3815 Walnut Street
Philadelphia, PA 19104-6196

Dr. Ronald Sternfels
Oak Ridge Assoc. Univ.
P.O. Box 117
Oak Ridge, TN 37831-0117

Dr. David E. Stone
Computer Teaching Corporation
1713 South Neil Street
Urbana, IL 61820

Dr. Patrick Suppes
Stanford University
Institute for Mathematical
Studies in the Social Sciences
Stanford, CA 94305-4115

Dr. Perry W. Thorndyke
FMC Corporation
Central Engineering Labs
1205 Coleman Avenue, Box 580
Santa Clara, CA 95052

Dr. Sharon Tkacz
Allen Corporation
209 Madison Street
Alexandria, VA 22314

Dr. Douglas Towne
Behavioral Technology Labs
University of Southern California
250 N. Harbor Dr., Suite 309
Redondo Beach, CA 90277

Major D. D. Tucker
HQMC, Code MA, Room 4023
Washington, DC 20380

Dr. Paul T. Twobig
Army Research Institute
ATTN: PERI-RL
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. Zita E. Tyer
Department of Psychology
George Mason University
4400 University Drive
Fairfax, VA 22030

Dr. Harold P. Van Cott
Committee on Human Factors
National Academy of Sciences
2101 Constitution Avenue
Washington, DC 20418

Dr. Kurt Van Lehn
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Frank L. Vicino
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Jerry Vogt
Navy Personnel R&D Center
Code 51
San Diego, CA 92152-6800

Dr. Thomas A. Warm
FAA Academy AAC934D
P.O. Box 25082
Oklahoma City, OK 73125

Dr. Beth Warren
BBN Laboratories, Inc.
10 Moulton Street
Cambridge, MA 02238

Dr. Diana Wearne
Department of Educational
Development
University of Delaware
Newark, DE 19711

Dr. Shih-sung Wen
Department of Psychology
Jackson State University
1400 J. R. Lynch Street
Jackson, MS 39217

Dr. Keith T. Wescourt
FMC Corporation
Central Engineering Labs
1205 Coleman Ave., Box 580
Santa Clara, CA 95052

Dr. Douglas Wetzel
Code 51
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Barbara White
School of Education
Tolman Hall, EMST
University of California
Berkeley, CA 94720

Dr. David Wilkins
University of Illinois
Department of Computer Science
1304 West Springfield Avenue
Urbana, IL 61801

Dr. Marsha R. Williams
Appl. of Advanced Technologies
National Science Foundation
SEE/MDRISE
1800 G Street, N.W., Room 635-A
Washington, DC 20550

S. H. Wilson
Code 5505
Naval Research Laboratory
Washington, DC 20375-5000

Dr. Robert A. Wisner
U.S. Army Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. Merlin C. Wittrock
Graduate School of Education
UCLA
Los Angeles, CA 90024

Mr. Paul T. Wobig
Army Research Institute
5001 Eisenhower Ave.
ATTN: PERI-RL
Alexandria, VA 22333-5600

Mr. Joseph Wohl
Alphatech, Inc.
2 Burlington Executive Center
111 Middlesex Turnpike
Burlington, MA 01803

Dr. Wallace Wulfek, III
Navy Personnel R&D Center
Code 51
San Diego, CA 92152-6800

Dr. Masoud Yazdani
Dept. of Computer Science
University of Exeter
Prince of Wales Road
Exeter EX44PT
ENGLAND

Dr. Joseph L. Young
National Science Foundation
Room 320
1800 G Street, N.W.
Washington, DC 20550

Dr. Uri Zernit
General Electric
Research & Development Center
Artificial Intelligence Program
PO Box 8
Schenectady, NY 12301